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(SELECTED ARTICLES)

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APPLICATION OF THE THEORY OF SIMILARITY TO TO THE EXPERIMENTAL INVESTIGATION OF THE WORK REGIMES OF GAS TURBINES

G. E. Kalinin

Similarity conditions of gas turbines are examined; similarity criteria for their work regimes on different working substances are proposed.

At present the theory of similarity is rightly winning a larger and larger place in the investigation of turbine engines as the scientific basis of the organization of the experiment. Based on the theory of similarity, criterion relations have been worked out for generalizing the results of tests and extending these results to turbine work-regimes not experimentally verified.

In some cases, however, when determining the indices of turbine performance in accordance with the results of testing it on a working substance different from the natural one, the theory of similarity cannot be used for investigating the turbines because of the lack of criterion equations for simulation on various working substances. This last is connected with the fact that of five criteria of similarity at present established and determining the turbine work-regime only

two may be used for the graphic representation of characteristic turbines. The remaining three, namely, the criteria of Reynolds (Re) and Prandtl (Pr) and the index of the adiabatic curve (k) must be the same in nature and in the model; but if any one of them differs, the independence in practice of the examined process from that criterion must be demonstrated. Values determining the physical properties of the working substance (viscosity, heat conductivity, compressibility) enter the criteria Re, Pr, and k. Consequently the demand for equality between the criteria Re, Pr, and k in nature and in the model means that the turbines, to which are applied the methods, based on the theory of similarity, of generalizing and extending the experimental data, must work on the same working substances. In addition, that means that the temperature and pressure of the working substance must be close in nature and in the model, since the physical properties of a gas change with a change in thermal parameters. For simulation on various working substances it must be possible to take $Re \neq$ idem, $Pr \neq$ idem, $k \neq$ idem, i.e., assume the independence of the process from these criteria.

If in fact the process is not related to any criterion it is called auto-simulating with respect to this criterion. At present it has been ascertained that when $Pr \geq 3 \cdot 10^5$ to $7 \cdot 10^5$ the process in the turbine may be considered auto-simulating with respect to the Reynolds number [1]. There are methods of accounting for the influence of the Re numbers on the characteristics of the turbine when $Re < 3 \cdot 10^5$. In cases met in practice the flow of gas in the flow-through part of turbine, expressed in the criteria used at present, cannot be considered auto-simulating also with respect to k. A change in the magnitude of k exerts an influence on the characteristics of the turbine

in all regimes. The matter of simulation when $k \neq$ idem, notwithstanding research done in this area, is not resolved and is an obstacle to simulation on various working substance.

In approaching the solution of this problem it is advisable at first to examine the conditions of similarity of work regimes of gas-turbine engines. The following may be referred to the equation defining the work of the gas in the turbine: gas-dynamic equations for compressible, viscous, and heat-conductive liquids [2]; energy and discontinuity equations connecting the parameters of the gas on entering and leaving the turbine with the useful work taken off the turbine rotor.

The gas-dynamics equations:

$$\frac{\gamma}{g}\cdot\frac{dc_\beta}{d\tau}=\frac{\partial p}{\partial x_\beta}+\frac{\partial}{\partial x_\beta}\left[\mu\left(\frac{\partial c_\nu}{\partial x_\beta}+\frac{\partial c_\beta}{\partial x_\nu}-\frac{2}{3}\frac{\partial c_\alpha}{\partial x_\alpha}\right)\right]+$$
$$+\frac{\partial}{\partial x_\beta}\left(\zeta\frac{\partial c_\alpha}{\partial x_\alpha}\right)-\frac{\gamma}{g}\cdot\frac{\partial\psi}{\partial x_\beta};$$
$$\frac{\partial\gamma}{\partial\tau}+\frac{\partial\gamma c_\alpha}{\partial x_\alpha}=0;$$
$$\gamma\frac{d}{d\tau}\left(i+\frac{c^2}{2g}+\frac{\psi}{g}\right)=\frac{\partial}{\partial x_\nu}\left\{\lambda\frac{\partial T}{\partial x_\nu}+c_\beta\left[\mu\left(\frac{\partial c_\beta}{\partial x_\nu}+\right.\right.\right.$$
$$\left.\left.\left.+\frac{\partial c_\nu}{\partial x_\beta}-\frac{2}{3}\frac{\partial c_\alpha}{\partial x_\alpha}\right)+\zeta\frac{\partial c_\alpha}{\partial x_\alpha}\right]\right\}+\frac{\partial p}{\partial\tau}+\frac{\gamma}{g}\cdot\frac{\partial\psi}{\partial\tau};$$
$$pv=RT;$$

the energy and discontinuity equations:

$$L_e=\frac{1}{A}(i_0-i_2)+\frac{c_0^2}{2g}-\frac{c_2^2}{2g};$$
$$\gamma_0F_0c_{0a}=\gamma_2F_2c_{2a},$$

where c is the absolute velocity of the gas (the index a designates the component of velocity parallel to the axis of the turbine); γ) specific weight; g) acceleration of the force of gravity; τ) time; μ) first coefficient of viscosity, taking displacement deformations into account; ζ) second coefficient of viscosity, taking expansion deformations into

account; ψ) potential of the force field; p) pressure; v) specific volume; R) gas constant; T) absolute temperature; L_e) work at the rotor axle; A) heat-equivalent of the physical work; i) heat content; F) area of a cross section; x_β, x_ν, x_α) coordinates of a point in space (three-dimensional space is under consideration, therefore β, ν, and α pass through the values 1, 2, and 3; corresponding to this the subscripts β, ν, α with vectors will assume the values 1, 2, and 3).

Instead of the energy equation the following equation may also be used:

$$A \cdot 75 N_i = \eta_{oi} G (i_0^* - i_2'),$$

where N_i) internal power of the turbine; G) consumption of gas; η_{oi}) internal efficiency of the turbine; i_o) full heat content of the gas before the turbine; i_2') heat content at the end of isentropic expansion.

The following may be referred to single-valued conditions of the process in the turbine (a turbine work-regime which has established itself is under consideration, i.e., a process without initial conditions): physical magnitudes characterizing the working substance, pressure and temperature of the working substance entering the turbine and pressure on leaving the turbine, the geometrical dimensions of the flow-through part of the turbine, the angles of entry of the stream into the vanes of the runner of the turbine (the angles between the vector of relative stream velocity in front of the runner and the vector of the circumferential velocity of the working wheel).

As a result of investigating the invariance to similar transformations of the enumerated equations, of examining the conditions of uniqueness, of using the method of substitution in forming criteria, and of excluding constant criteria, we may note the following criteria determining the work regime (when auto-simulation with respect to Re

and Pr is assumed):

$$\frac{u^2}{kgRT_0} \sim \frac{u^2}{kRT_0}, \frac{p_2}{p_0}, \frac{k}{k-1}, \qquad (1)$$

where u is the circumferential velocity; and the ascertainable criteria are

$$\frac{A\,75N_i}{Gi_0}\left(\text{ or } \frac{N_i}{Gi_0}\right), \eta_{oi} \text{ etc.}$$

In the quoted system the criterion $\frac{k}{k-1}$ does not differ in principal from the existing criterion k = idem, but it reflects the latter's physical significance more closely. It, like the criterion k=idem, demands equality in the values of the index of the adiabatic curve k in nature and in the model.

In solving the simulation problem when k ≠ idem it is natural to turn to the method of approximate simulation. This method recommends excluding from the criterion relation a criterion of little effect and, by means of a practical check, confirming the suitability of the thus abbreviated criteria. However, the criterion $\frac{k}{k-1}$ in the system of defining criteria (1) is not of little influence. Simple exclusion of it from the standard relations

$$\left.\begin{aligned} \eta_{oi} &= f\left(\frac{p_2}{p_0}, \frac{u^2}{kRT_0}, \frac{k}{k-1}\right); \\ \frac{A\,75N_i}{Gi_0} &= f\left(\frac{p_2}{p_0}, \frac{u^2}{kRT_0}, \frac{k}{k-1}\right) \text{ etc.} \end{aligned}\right\} \qquad (2)$$

leads to substantial errors.

It would seem impossible to use the method of approximate simulation. The situation changes, however, if we prepare the criterional relation in advance, which we shall call generalization of the criteria. This preparation can be done based on the production of criteria or the quotient of their division also being a criterion. Then the criteria which it is proposed to use for approximate simulation prove

capable of union with the excluded criterion, in our case with the criterion $\frac{k}{k-1}$. The union must be carried out taking into consideration the influence of the individual criteria and value complexes on the relation to be elaborated, and also observing the rules for their transformation.

The most successful result of using the method of generalizing the criteria to the relations (2) is obtained with the criterion $\frac{A \cdot 75N_i}{Gi_o}$. In this case the value of $i_o = \frac{k}{k-1} ART_o$ is proportional to the criterion $\frac{k}{k-1}$. Using the method of generalizing the criteria to the criterion $\frac{A \cdot 75N_i}{Gi_o}$, we obtain

$$\frac{A \cdot 75N_i}{G\frac{k}{k-1}ART_0} \cdot \frac{k}{k-1} = \frac{A \cdot 75N_i}{GART_0} \sim \frac{A \cdot 75N_i}{GRT_0},$$

the value of which does not depend on the value of k.

In conformity with the principle of the theory of similarity and dimensionality the number of criteria after transformation must not change. Therefore together with the generalized criterion $\frac{A \cdot 75N_i}{Gi_o}$, $\frac{k}{k-1}$ also enters the standard equation. Consequently the standard equation will have the form:

$$\frac{A \cdot 75N_i}{GRT_0} = f\left(\frac{p_2}{p_0}, \frac{u^2}{kRT_0}, \frac{k}{k-1}\right). \tag{3}$$

The adaptability of the relationship

$$\frac{A \cdot 75N_i}{GRT_0} = f\left(\frac{p_2}{p_0}, \frac{u^2}{kRT_0}\right) \tag{4}$$

for simulating turbine work-regimes on different working substances was confirmed in particular by treating the experimental data in the criteria of (4) on tests of an axial single-stage turbine in air (k = 1.12), CO_2 (k = 1.27), and CCl_4 (k = 1.12) cited in a certain

work [3]. We should note that CO_2 and CCl_4 in the tests had a certain admixture of air. The treatment showed that the turbine characteristics in the criteria of similarity in (4), referring to the turbine work-regimes on various working substances with differing values of the index of the adiabatic curve, coalesce practically completely when the two determining criteria u^2/kRT_0 and p_2/p_0 are equal (Fig. 1). Contrariwise, treating the experimental data of the tests of the same turbine in air and in CO_2 in the criteria

$$\eta_{oi}=f\left(\frac{p_2}{p_0},\ \frac{u^2}{kRT_0}\right);$$
$$\frac{A\,75N_i}{G\frac{k}{k-1}ART_0}=f\left(\frac{p_2}{p_0},\ \frac{u^2}{kRT_0}\right)$$

etc. gives a 10-15% divergence in characteristics (Figs. 2, 3). The graphs confirm the adaptability of the standard relationship in (4) for simulation when $k \neq$ idem.

Thus the criterion relation in (4) may be recommended for use in simulating work regimes of turbine engines on different working substances with differing values of the index of the adiabatic curve. Representing the turbine characteristics in the criteria of similarity in (4) enables us, from the results of testing the turbine for one of the assimilated compositions of the working substance, to determine the indices of its work in various set-ups with arbitrarily assigned composition for the working substance (e.g., when investigating the effect of water injection in the gas tract of gas-turbine units on the power of the turbine, when developing atomic gas-turbine transportation units, etc.), which essentially simplifies a number of investigations of power units with turbine engines.

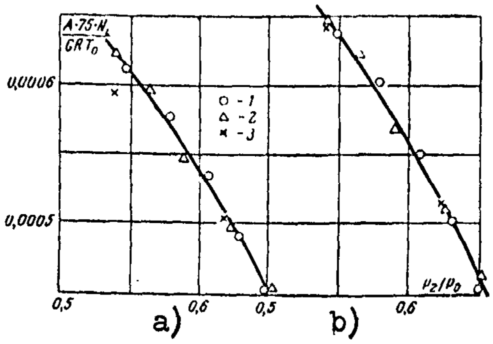

Fig. 1. Turbine characteristics in similarity criteria

$$\frac{A\cdot 75N_i}{GRT_0} = f\left(\frac{p_2}{p_0}, \frac{u^2}{kRT_0}\right),$$

constructed from the results of testing a turbine on various working substances.

$$a - \frac{u^2}{kRT_0} = 0{,}7;\ б - \frac{u^2}{kRT_0} = 1{,}05.$$

1) air; 2) CO_2; 3) CCl_4

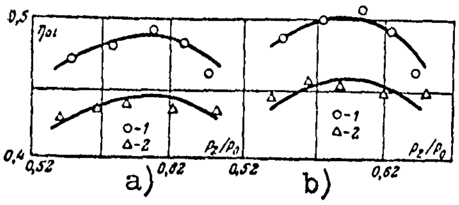

Fig. 2. Turbine characteristics in similarity criteria

$$\eta_{oi} = f\left(\frac{p_2}{p_0}, \frac{u^2}{kRT}\right),$$

constructed from results of testing a turbine on various working substances (a, b — see Fig. 1).
1) air; 2) CO_2

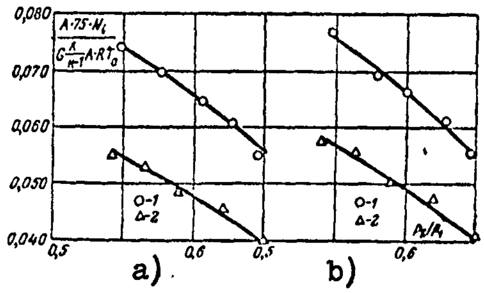

Fig. 3. Turbine characteristics in similarity criteria

$$\frac{A\cdot 75N_i}{G\frac{k}{k-1}ART_0} = f\left(\frac{p_2}{p_0}, \frac{u^2}{kRT_0}\right),$$

constructed from results from testing a turbine on various working substances (a, b — see Fig. 1).
1) air; 2) CO_2

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METHODS AND CERTAIN RESULTS OF THE MEASUREMENT OF THE CRITICAL LOAD DURING THE TRANSITION FROM FILM TO BUBBLE BOILING

Prof. B. S. Petukhov, Doctor of Technical Sciences,

and S. A. Kovalev, Engineer

Moscow Institute of Power Engineering

The measurement of the second critical loads during the boiling of a liquid is considered, the results of an experimental study are presented, and a method of calculating the stability of the film and bubble regimes of boiling is proposed.

In present-day steam generators and atomic reactors, which operate at high thermal loads, operating regimes accompanied by film boiling are possible. An exact knowledge is needed of the so-called critical heat loads, at which a change occurs in the boiling regime of a liquid on the heating surface, in order to achieve stable operation of the heating surface within given temperature limits.

The many investigations conducted both in the Soviet Union and abroad have made it possible to accumulate a great deal of experimental material concerning critical loads during the transition from bubble to film boiling, q_{cr1}.

Critical loads in the transition from film to bubble boiling have been much less studied. Certain investigations in recent years, carried out with the aid of high-speed motion pictures, and theoretical treatments indicate that the termination of film boiling occurs upon reaching the second critical load q_{cr2}, as a result of a loss of the stability of motion of the vapor film, a stability related to the stability of the capillary waves at the interface of the liquid and vapor phases. Certain experimental data on the second critical loads are also available.* However, these data are very scanty and show essential discrepancies. Such a situation is, to a certain extent, related to the absence of a sufficiently developed method which would permit reliable determination of the second critical loads. On the basis of an analysis of the possible methods of measuring q_{cr2}, this article recommends one which was developed at MEI (Moscow Institute of Power Engineering) and which has a number of important advantages.

The simplest and most convenient method under laboratory conditions is that of electrical heating, in which a current is passed directly through the working element of the apparatus. In the case of electrical heating, film boiling may be obtained by two methods. By gradually increasing the thermal load and passing through the first crisis, a transition to film boiling is achieved. After attaining steady film boiling the load is reduced, until reverse transition to the bubble regime of boiling takes place. This is the load taken as q_{cr2}. The basic shortcoming of this method lies in the fact that during the transition to film boiling under large

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* M. V. Borishanskiy. Article in the collection "Problems of Heat Transfer During a Change in the Aggregate State of a Substance." Gosenergoizdat, 1953.

thermal loads, the temperature of the surface increases sharply. Therefore such materials as nichrome and various alloy steels melt, and their use may thus lead to the destruction of the surface. This method requires the use of refractory metals or graphite.

However, through electrical heating it is possible to obtain a film regime of boiling, skipping the first crisis, at relatively low temperatures and heat loads on the heating surface. To do this, the heating surface is warmed up by an electric current in the vapor phase to a temperature higher than the temperature of the second boiling crisis $t = t_s + t_{cr2}$ and is then lowered into the liquid phase under a thermal load somewhat greater than that of the second critical load. For example, in order to obtain film boiling in water at atmospheric pressure, it is sufficient to heat the surface to only 350 - 400° C.

The method of electrical heating with transition through the first critical load was used in the work of V. M. Borishanskiy in an investigation of the second critical loads of water, isooctane, and benzene under conditions of free convection at pressures from 1 to 16 atm abs. Graphite rods with diameters of 2.2 mm, secured in copper clamps, were used as the experimental heating surfaces. In these experiments it was established, in particular, that the second critical load for water at atmospheric pressure is $2 \cdot 10^5$ kcal/m^2 · hr.

It should be noted that in the experiments of V. M. Borishanskiy there is no doubt that significant leakages of heat through the ends of the graphite rods took place, and these might have substantially distorted the values of the second critical load. As an example, let us consider a sufficiently long rod, the ends of which are secured in massive copper current carriers, while on the surface, film boiling

is maintained by electrical heating. Since the ends of the rod will have a low temperature corresponding to the temperature of the massive clamps, at these places on the surface of the rod there must be a bubble regime of boiling. Thus, near the ends of the rod there will be zones with two regimes of boiling — bubble and film — with very different heat-transfer coefficients and sharply differentiated surface temperatures. As a result of this simultaneous occurrence of two regimes of boiling at the ends of the rod, with a reduction of the load , the film starts to recede to the center of the rod long before the attainment of the second critical density of the heat flux q_{cr2}, on account of a reduction in the temperature of the heating surface. Regardless of the length of the rod and the relation between the quantity of heat given off from the surface and the end losses, this process will continue until the film is removed from the entire surface of the rod. Under these conditions (on account of a reduction in the temperature by axial heat flows) the local heat loads from the surface in the zone of film removal will be significantly less than the heat loads obtained in the experiments and calculated according to the electrical power input over the entire surface of the rod. Consequently, on a sufficiently long rod it is possible to study heat transfer even in the presence of end losses, but it is not possible to study critical thermal loads.

For these reasons the data obtained by V. M. Borishanskiy and other authors by the methods described can hardly be considered trustworthy. They undoubtedly require verification. For this purpose special experiments were carried out by MEI.

The experiments were carried out with distilled water at atmospheric pressure under conditions of free convection. Horizontal wires

and tubes, through which an electric current was passed, served as the heating surface. In order to obtain film boiling, the above-described method of heating the specimen to the vapor phase beforehand was used.

Special consideration was given to obtaining a constant temperature field throughout the length of the specimen. Since it was not possible to secure the wires or tubes in such a way that there would be no heat leakages in the current conductors, the copper clamps were withdrawn into the vapor phase (Fig. 1). This made it possible to eliminate the temperature irregularity along the part of the heating element located in the liquid phase by selecting the height of the protruding ends.

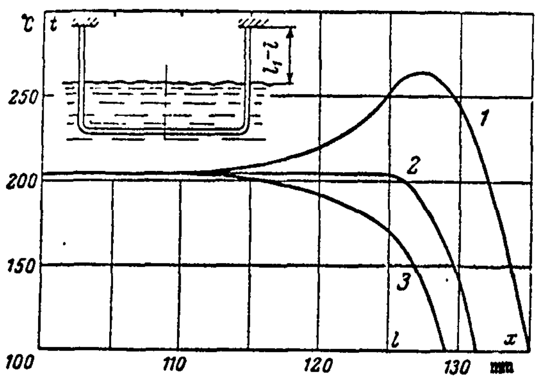


Fig. 1. The temperature distribution over the length of a stainless-steel specimen with a diameter of 2 mm at q = = 40 · 10^3 kcal/m^2 · hr.

$1-l_1-l$ 10 мм; $2-l_1-l=(l_1-l)_0=6{,}3$ мм; $3-l_1-l=4$ мм.

In order to calculate the temperature distribution along the length of the specimen, we shall assume that the temperature does not vary over the cross section of the specimen. Then the differential equation of the temperature field, which is easily obtained from the heat balance, has the form:

$$\frac{d^2t}{dx^2}+\beta t+\gamma=0;$$
$$\beta=\frac{0{,}86I^2b}{f^2\lambda}-\frac{\alpha u}{f\lambda};\qquad(1)$$
$$\gamma=\frac{0{,}86I^2a}{f^2\lambda}+\frac{\alpha u t_s}{f\lambda},$$

where t = temperature of the wire or tube at a given point (°C);
t_s = saturation temperature (°C);
$\rho = a + bt$ = resistivity (ohm.m);
I = current (amps);

α = heat-transfer coefficient (kcal/m^2 · hr · $^\circ$C);
λ = coefficient of thermal conductivity (kcal/m · hr · $^\circ$C);
f = cross-sectional area of the specimen (m^2);
u = perimeter of the specimen (m);

Since the constants β and ν contain the heat-transfer coefficient, they will have different numerical values for elements of the surface located within the liquid and vapor phases. Indeed, for elements of the surface located in the liquid, where the heat-transfer coefficient is high even for film boiling, $\beta < 0$, while for elements of the surface located in the vapor phase, where α is small, usually $\beta \geq 0$. Accordingly, the solutions of Eq (1) will have the following form:

for elements of the surface of the specimen located in the liquid ($\beta < 0$) i.e., over the interval $0 \leq x \leq l$,

$$t = D_1 \frac{\mathrm{sh}\sqrt{\beta}\,x}{\mathrm{sh}\sqrt{\beta}\,l} + D_2 \frac{\mathrm{ch}\sqrt{\beta}\,x}{\mathrm{ch}\sqrt{\beta}\,l} + \frac{\gamma}{\beta};\ ^* \tag{2}$$

* ch = cosh and sh = sinh

for elements of the surface of the specimen located in the vapor phase ($\beta > 0$) i.e., over the interval $l < x \leq l_1$

$$t = C_1 \frac{\sin\sqrt{\beta_1}(x-l)}{\sin\sqrt{\beta_1}(l_1-l)} + C_2 \frac{\cos\sqrt{\beta_1}(x-l)}{\cos\sqrt{\beta_1}(l_1-l)} - \frac{\gamma_1}{\beta_1}. \tag{3}$$

Here the total length of the specimen is taken equal to $2l_1$, while the length of the section of the specimen immersed in the liquid is $2l$.

In the particular case where $\beta = 0$ the variation in the temperature will be parabolic.

In order to find the constants of integration, it is necessary to assign boundary conditions.

Since the temperature distribution must be symmetrical, at the center of the specimen (i.e., for x = 0) dt/dx = 0 (Fig. 1).

The temperature of the ends of the specimen is equal to the temperature of the clamps t_1. In other words, for $x = l_1$, $t = t_1$.

It may be easily measured experimentally and is usually close to the saturation temperature.

In order to obtain a description of the temperature field over the entire length of the specimen, it is necessary to reconcile the solutions to Eqs. (2) and (3), i.e., for x = l the following conditions must be satisfied:

$$|t_{x<l}|_{x=l} = |t_{x>l}|_{x=l}; \quad \left|\frac{dt_{x\le l}}{dx}\right|_{x=l} = \left|\frac{dt_{x>l}}{dx}\right|_{x=l}.$$

After simple transformations we arrive at the values of the constants in Eqs. (2) and (3):

$$\left.\begin{aligned} &D_1 = 0; \\ &D_2 = \left[\left(t_1 + \frac{\gamma_1}{\beta_1}\right)\frac{1}{\cos\sqrt{\beta_1}(l_1 - l)} - \frac{\gamma}{\beta} - \frac{\gamma_1}{\beta_1}\right] A; \end{aligned}\right\} \tag{2a}$$

$$\left.\begin{aligned} C_1 = {} & \left[\left(t_1 + \frac{\gamma_1}{\beta_1}\right)\sqrt{\frac{\beta}{\beta_1}}\,\mathrm{th}\sqrt{\beta}l\cdot\mathrm{tg}\sqrt{\beta_1}(l_1 - l) - \right. \\ & \left. -\left(\frac{\gamma}{\beta} + \frac{\gamma_1}{\beta_1}\right)\sqrt{\frac{\beta}{\beta_1}}\,\mathrm{th}\sqrt{\beta}l\sin\sqrt{\beta}(l_1 - l)\right] A; \\ C_2 = {} & \left[t_1 + \frac{\gamma_1}{\beta_1} + \left(\frac{\gamma}{\beta} + \frac{\gamma_1}{\beta_1}\right)\sqrt{\frac{\beta}{\beta_1}}\,\mathrm{th}\sqrt{\beta}l \times \right. \\ & \left. \times\sin\sqrt{\beta_1}(l_1 - l)\right] A, \end{aligned}\right\} \tag{3a}$$

where

$$A = \left[1 + \sqrt{\frac{\beta}{\beta_1}}\,\mathrm{th}\sqrt{\beta}l\,\mathrm{tg}\sqrt{\beta_1}(l_1 - l)\right]^{-1}.$$

(note: th = tanh and tg = tan)

Analysis of Eqs. (2) and (2a) indicates that it is possible to select a length of the protruding ends $(l_1 - l)_0$, such that the second term on the right-hand side of Eq. (2) goes to 0 and the temperature on the entire section of the specimen immersed in the liquid will be the same. Assuming $D_2 = 0$, from Eq. (2a), we find:

$$l_1 - l = \frac{\arccos\dfrac{t_1 + \frac{\gamma_1}{\beta_1}}{\frac{\gamma}{\beta} + \frac{\gamma_1}{\beta_1}}}{\sqrt{\beta_1}}. \tag{4}$$

It is clear from simple physical considerations that if the section of the specimen protruding from the liquid has a length greater than $(l_1 - l)_0$, then the specimen in the vapor phase will be superheated, and if it is smaller than $(l_1 - l)_0$, then the section of the specimen located in the liquid will be cooled as a result of heat flowing off into the clamps. The same results follow from Eqs. (3) and (3a). As an example, Fig. 1 shows the temperature distribution along a two-millimeter stainless-steel wire, calculated according to Eqs. (2a) and (3a) for three values of $l_1 - l$.

The graphs shown in Fig. 1 clearly indicate that the relatively small deviations of $l_1 - l$ from $(l_1 - l)_0$ significantly change the temperature field of the specimen in the vapor phase and on a small section of the specimen in the liquid near the free level, but have practically no affect on the entire central part of the specimen. Therefore, experiments on the investigation of q_{cr2} may be carried out with protruding ends longer than $(l_1 - l)_0$. In this case removal of the film will always begin in the central part of the specimen.

A profile with a monotonic reduction of temperature toward the ends for $l_1 - l < (l_1 - l)_0$ as was demonstrated above, is completely unsuitable for a study of q_{cr2}, but a constant profile for $l_1 - l =$ $= (l_1 - l)_0$ is difficult to realize. If in the process of the experiments it should turn out that the calculated height $(l_1 - l)_0$ was underestimated and the removal of the film begins at the points where the specimen emerges from the liquid, then it may be easily detected visually and corrected by changing the height of the protruding ends.

Figure 2 shows a schematic of the apparatus. It consists of a stainless-steel tank which has a window in the front wall for visual observations. The experimental specimen is secured in copper clamps which are mounted on a textolite panel and insulated from the steel cover of the tank by textolite bushings. During the experiment the panel can easily be moved upwards; then the specimen is in the vapor phase. The water in the apparatus is maintained at the saturation temperature by an electric heater located beneath the bottom of the tank. In order to avoid the influence of convection currents of the liquid on the vapor film surrounding the specimen there is a special shield between it and the bottom. In order to measure the voltage drop over the experimental section of the specimen, two potentiometer probes 0.2 mm in diameter were welded to its upper generatrix at a distance of about 100 mm from each other. Specimens with diameters of 0.5 and 1.4 mm were prepared from constantan wire, so as not to distort the temperature field with the potentiometer wires. In this case the thermal loads were determined from the current and the resistance.

The experimental procedure was as follows. After the water was brought to a boil, the specimen was raised to the vapor phase and was heated by an electric current to a temperature of $350-400^{\circ}$. The heated specimen with a thermal load greater than the second critical load was lowered into the water, and film boiling set in on its upper surface. The thermal load was reduced by small stages, the magnitude of which did not exceed 1% of the load. After each reduction of the load and attainment of a steady-state regime, measurements were made of the current and the voltage drop over the experimental section. The regime at which removal of the film sets in was considered to

be the critical regime corresponding to the second critical load. Such regimes were often repeated. Control experiments were conducted systematically, in which film-boiling regimes immediately preceding the crisis were maintained for 10-20 minutes. These experiments served as good confirmation of the reliability of the determination of q_{cr2}.

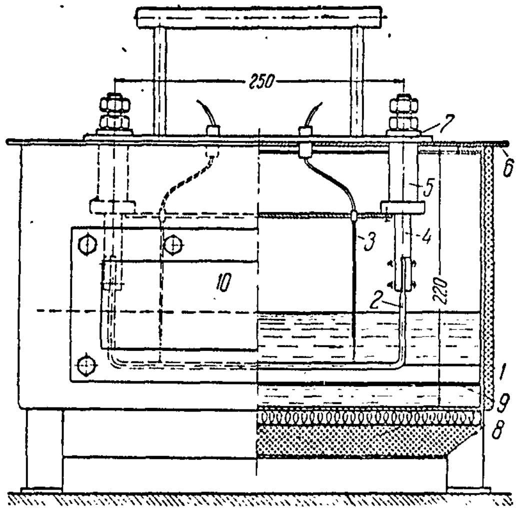


Fig. 2. Experimental apparatus; 1) tank, s = 380 x 190 mm; 2) experimental specimen; 3) potentiometer leads; 4) current carriers; 5) insulating bushings; 6) tank cover; 7) textolite panel; 8) electric heater; 9) protective shield; 10) window.

In each experiment the location of film removal was monitored visually. Usually the film began to come off at an arbitrary point of the horizontal part. The beginning of film removal from the ends of the specimen attested to the presence of heat leakages along the specimen, and such experiments were rejected.

During the experiments the following picture of film removal was observed. From thin wires the film comes off rapidly (fractions of seconds) with a characteristic crackling. The film comes off

slowly from thick stainless-steel pipes with a great heat capacity and we may readily observe how at critical loads the film-boiling regime is replaced by unstable film oscillations, which correspond to a transition region and which then give way to the bubble-boiling regime.

The experimental results are presented in Fig. 3 in the form of a dependence of the second critical thermal load on the diameter of the specimen (in logarithmic coordinates). A study of the experimental data shows that the second critical load decreases with an increase in the diameter of the specimen. A dependence of the critical loads on the material of the surface was not revealed. The measurement results are presented in the table.

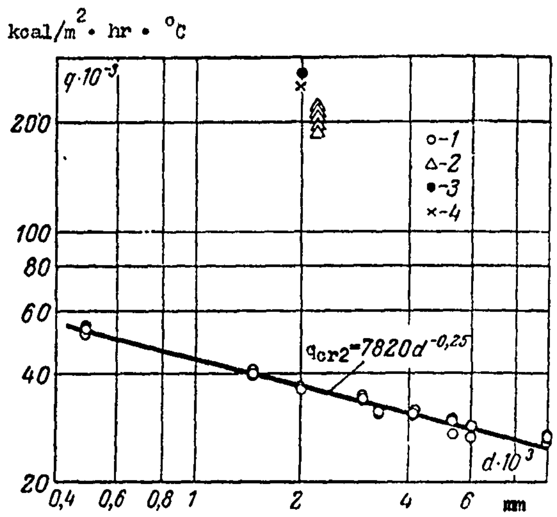


Fig. 3. Dependence of the critical load on the diameter of the specimen: 1) q_{cr2}, data of the authors; 2) data of V. M. Borishanskiy; 3) q_{equi} experimental; 4) q_{equi} calculated.

The values of q_{cr2} obtained make it possible to determine by calculation the thermal-load values of practical interest, at which the bubble and film regimes of boiling will be in equilibrium on a

wire or tube. Let us call this load the equilibrium load (q_{equi}). For heat flows greater than q_{equi} film-boiling regimes which arise accidentally will propagate over the entire surface of the specimen. For loads less than q_{equi} and with the simultaneous existence of film and bubble boiling on the surface of the specimen, film removal occurs as a result of axial thermal outflows.

In order to calculate the equilibrium load, let us use the following model. Developed bubble boiling is maintained on the outer surface of a tube of length $2l$. Let us find the thermal loads at which both regimes of boiling will be stable.

Diameter of specimen	$q_{cr2} \cdot 10^{-3}$, kcal/m^2·hr	Material of Specimen	Comment
0,493	53,7 52,4 51,7	Constantan	Wire
1,46	40,0 40,0 41,0	"	"
1,98	36,7 36,4	Stainless Steel	"
3,04	34,0 34,2 34,1 34,5	"	Tube, d = 0,5mm
3,33	31,3 30,8 31,5 31,5	"	Tube, d = 0,2mm
4,17	30,7 30,9 31,9	"	Tube d = 0,2mm
5,39	27,8 29,5 30,6	St. 3	Rod
6,04	28,4 28,2 26,4	Stainless Steel	Tube, d = 1,0mm
10,15	26,2 26,6 26,6	"	Tube, d = 1,0mm

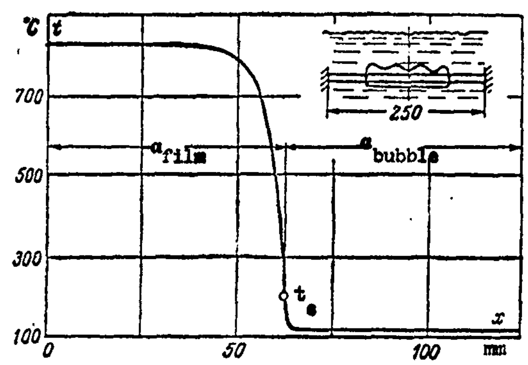


Fig. 4. Temperature distribution over the length of a specimen under an equilibrium load.

It is known that in the case of film boiling the dependence of the heat transfer on the load is slight. Therefore it may be assumed that in the region of film boiling the heat-transfer coefficients are constant over the length of the tube and are equal to α_{film}. As for the transition region and the region of bubble boiling, the heat-transfer coefficients may vary over the length of the tube. However, for simplicity of calculation, we shall take the heat-transfer coefficients in both of these regions as being equal to the heat-transfer coefficients for ordinary bubble boiling α_{bubble} at a given load. Since the heat-transfer coefficients for the film and bubble regimes of boiling are different, the temperature field of the specimen is described by two equations of type (2), which must be reconciled at the point of change in the boiling regime with respect to temperatures and temperature gradients. As the boundary conditions we shall assume that the temperature gradients in the center of the tube and in the zone of bubble boiling far from the interface are equal to zero. We shall also consider as given the film-removal temperature, which is determined by the experimental values of the second critical load $t_c = t_s + \frac{q_{cr_2}}{\text{film}}$.

The temperature distribution in the region of film removal, thus calculated, is shown in Fig. 4. From the general solution we obtain the following equation:

$$t_{\text{к}} = \frac{\frac{\gamma_1}{\beta_1} + \frac{\gamma}{\beta}\sqrt{\frac{\beta}{\beta_1}}\,\mathrm{cth}\sqrt{\beta_1}(l-l_1)\,\mathrm{th}\sqrt{\beta}\,l_1}{1+\sqrt{\frac{\beta}{\beta_1}}\,\mathrm{cth}\sqrt{\beta_1}(l-l_1)\,\mathrm{th}\sqrt{\beta}\,l_1}, \;* \qquad (5)$$

*cth = coth and th = tanh

where $\frac{\gamma}{\beta} \approx t_{film}$, the temperature of the specimen in the region of film boiling in the absence of axial heat flows;

$\frac{\gamma_1}{\beta_1} \approx t_{bubble}$, the temperature of the specimen in the region of bubble boiling in the absence of axial heat flows.

For a sufficiently long tube or wire, the equation becomes simply:

$$\frac{t_0 - t_{film}}{t_{bubble} - t_{film}} = \frac{1}{1 + \sqrt{\frac{\beta}{\beta_1}}}. \qquad (6)$$

If the electrical resistance of the tube does not depend on the temperature, Eq. (6) assumes the form:

$$\frac{t_0 - t_{film}}{t_{bubble} - t_{film}} = \frac{1}{1 + \sqrt{\frac{\alpha_{film}}{\alpha_{bubble}}}}. \qquad (7)$$

Using Eq. (7) and the relationships $q_{equi} = \alpha_{film}(t_{film} - t_s) = \alpha_{bubble}(t_{bubble} - t_s)$ and $\alpha_{bubble} = f(t_{bubble} - t_s)$ it is easy to obtain t_{film} and the equilibrium load. For a two-millimeter wire with $\alpha_{bubble} = 2 \cdot 10^4$ and $\alpha_{film} = 400$ kcal/m^2 · hr · °C (α_{film} taken according to data of a specially conducted experiment) we obtain from Eq. (7) $q_{equi} = 254 \cdot 10^3$ kcal/m^2·hr.

The results of the calculation were verified experimentally. The experiments were conducted on a horizontally stretched nichrome wire 250 mm long and 2 mm in diameter. In order to obtain film boiling, the wire was heated in the vapor phase and then plunged into the liquid phase. The load was gradually reduced, until the film began to come off the ends of the wire. When the film covered about 1/3 of the length of the wire, a load was selected at which film removal ceased and the interface between the regimes of boiling became stationary. This load was taken as q_{equi}. When the load was increased, the film slowly spread out over the entire surface, while with a decrease in the load further removal of the film occurred. The experimental results ($q_{equi} = 276 \cdot 10^3$ kcal/m^2·hr) corroborate the calculated value of the equilibrium load.

Thus, in order to calculate equilibrium thermal loads, it is sufficient to know the exact values of the heat-transfer coefficients

and the second critical loads. Analogous calculations of equilibrium loads may be made for a heating surface of any other shape.

The experimental data obtained by V. M. Borishanskiy, as follows from Fig. 3 and also from the nature of the method employed, corresponds more to an equilibrium thermal load than to the second boiling crisis.

Conclusions

1. A method has been developed for the measurement of the second critical loads during the boiling of a liquid under conditions of free convection, a method which makes it possible to obtain reliable experimental data.

2. Measurements were made of the second critical load on horizontal tubes and wires with diameters ranging from 0.5 to 10 mm for water under conditions of free convection in a large volume. It is shown that the published data concerning second critical loads exceed the actual values several times over.

3. It is shown that the second critical load decreases with an increase in the diameter of the wire or tube.

4. The material of the heating surface was not observed to have any effect on q_{cr2}.

5. It was shown that the experimental values of q_{cr2} obtained make it possible to calculate the equilibrium loads which constitute the upper limit of stable bubble boiling and the lower limit of stable film boiling on a given surface.

METHODS OF GENERALIZING EXPERIMENTAL DATA ON CONVECTIVE HEAT TRANSFER DURING THE MOVEMENT OF GAS IN THE INITIAL REGION OF A CONDUIT

Prof. S. I. Kosterin, A. I. Leont'yev,

and V. K. Fedorov

A new method for generalizing the experimental data on convective heat transfer in the turbulent boundary layer of a gas is proposed. A universal law of heat transfer for the turbulent boundary layer of a compressed gas is derived.

Research on the processes of convective heat transfer and of resistance in the motion of a gas in relatively short cylindrical conduits is at present timely enough from both the practical and the scientific point of view. There are sufficiently reliable analytical solutions for the case of laminar boundary layer in the initial region of a cylindrical conduit. Methods of calculating this layer,

however, in elaborating which experimental investigations exert great influence, are of great practical interest. We cannot consider as successful the methods for this sort of generalization recommended in the literature [1-3].

One article [1] cites interesting experimental data on heat transfer and on resistance in cases of sufficiently intense heating of the gas. The method of generalization adopted by the authors, however, is of a very provisory nature; and the proposed criterional equations have a limited area of application. Proceeding from elementary considerations we may show that the criterional equation of heat transfer in the motion of a compressed gas in the initial section of a cylindrical conduit has the form

$$Nu = f\ (Re,\ Pr,\ \overline{x},\ M,\ \overline{T}_w). \qquad (1)$$

The authors [1] write Eq. 1 in the form

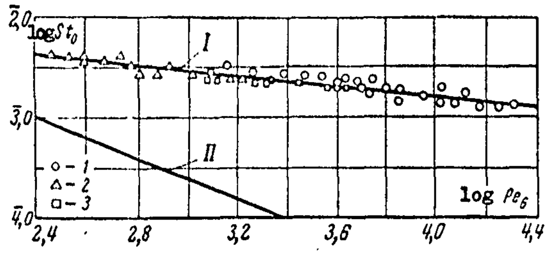
$$Nu = c\ Re^m Pr^{0.4} \left(\frac{T}{T_w} \right)^p, \qquad (2)$$

where the coefficients c, m, and p for the initial section are functions of x/D and these functions are derived by experimentation and presented in the form of separate graphs. It is quite clear that the proposed method of calculation will give correct results only for those heat-supply relationships which occurred in the experiments of the authors of the article [1]. We should also note that under the common influence of several criteria it is difficult to fix the effect of each criterion separately; and the nature of spread of the experimental points near the path of the criterional equation may not be used for final evaluation of the criterional equation's correctness, since under these conditions mutual compensation of errors is possible. The

one-dimensional flow chart for the gas in the initial section of the conduit adopted in the article [1] does not correspond to the actual picture of the process and can lead to incorrect conclusions. In particular, the very hazardous conclusion that, when isothermal conditions are lacking, the basic relationship of the hydrodynamic theory of heat transfer fails is the result of treating the experimental data on the coefficient of friction in accordance with this one-dimensional flow chart. If we treat the data in accordance with the two-dimensional flow chart, no failure of the similarity is observed. We should also note that the proposed criterional equation is true only for those conditions at the conduit entry which occurred in the experiments in the article [1].

An interesting method for generalizing the experimental data on heat transfer in the initial section of a cylindrical conduit is proposed in another article [2]. This method is convenient for treating the experimental data and the practical calculations when a law of heat supply along the length of the conduit is given. The principal defect of this method is the necessity of deriving its criterional equation for every heat-supply relationship.

Experimental research on heat exchange in conduits at supersonic gas velocities when entering the conduit is of great interest in other articles [3, 4]. In this case we must take into consideration the effect of gas compressibility on the coefficients of heat transfer and this substantially complicates criterional treatment of the experimental data. We should note that at supersonic velocities of the gas on entrance into the conduit we are unable to obtain supersonic velocities of gas flow for a great extent and therefore it is almost always necessary to to deal with the region of hydrodynamic and thermal stabilization. Besides that, there arise essential difficulties connected with



The dependence of St_0 on Pe_θ for the initial section of a conduit. Data from 1) Lel'chuk and Dyadyakin [1]; 2) Petukhov, Detlav and Kirillov [11]; 3) Bradfield and Decoursin [10]. Law of heat transfer for I) turbulent boundary layer $St_0 = \dfrac{0.014}{Re_\theta^{0.25} Pr^{0.5}}$;

II) laminar boundary layer $St_0 = \dfrac{0.22}{Pe_\theta Pr^{1/3}}$.

obtaining an undisturbed supersonic stream entering the conduit; therefore the accuracy of the experiments under these conditions is substantially lower than in subsonic velocities of gas motion. In the article [4] the bulk of the experimental points are distributed in the transitional region; therefore the authors have renounced criterional treatment of the experimental data.

One article [3] cites the extensive experimental material on the coefficients of heat transfer at supersonic velocities of gas motion in a conduit. Here the authors attempt to generalize the experimental data in the form of criterional equations based on one- and two-dimensional simulations of flow in the conduit. Under these conditions the number of identifying criteria mutually influencing the local Nusselt criteria increases to four (Re_D, $\overline{x}$, $\overline{T}_w$, M). Experiments have been conducted under comparatively slight intensities of heat transfer; therefore the criteria Re_D, $\overline{x}$, and M exert a basic influence on the change in the coefficients of heat transfer along the length of the conduit; and in this the distribution of M along the length is a function of Re_D. It is extremely hazardous to say that under these complex conditions the final criterion equation takes into consideration the effect of every criterion separately. In particular, the authors of the article [3], when determining the influence of compressibility, assume in essence that the effect of criterion $\overline{x}$ on the local values of the Nusselt criteria is the same at both subsonic and supersonic velocities, which is not in accord with the realities of the situation, since the development of the boundary layer along the length of the conduit is essentially a function of M on entry.

Thus we may infer that at present we have no reliable and physically based method of generalizing experimental data on convective

heat transfer in gas motion in the initial section of a conduit.

It is quite natural to use the theory of local simulation in investigating these heat-transfer processes. Two works [5, 6] expound the basic ideas of this theory. According to this theory the aim of the experiment is to establish the laws of heat transfer and resistance in the turbulent boundary layer; but the effect of the different external conditions (distribution of pressures, wall temperatures, thermal currents, etc.) are accounted for by the boundary-layer equations. The equation for the thermal boundary layer for the movement of a gas in the initial section of a conduit may be written in the following form:

$$\frac{d\mathrm{Pe}_\theta}{dx} + \mathrm{Pe}_\theta \frac{dt_\theta}{t_0\,dx} = \mathrm{St}\,\mathrm{Pe}_D; \tag{1}$$

$$\mathrm{Pe}_\theta = \frac{u_0 \theta}{a_{00}}; \quad t_0 = T_W^* - T_W \cdot$$

$$\theta = \int_0^{\frac{D}{2}} \frac{\rho u}{\rho_0 u_0} \left(\frac{T_{00} - T_W}{T_W^* - T_W} - \frac{T^* - T_W}{T_W^* - T_W} \right) dy;$$

$$\mathrm{St} = \frac{q_W}{\rho_0 u_0 c_p (T_W^* - T_W)}; \quad \mathrm{Pe}_D = \frac{u_0 D}{a_{00}};$$

$$\bar{x} = \frac{x}{D}; \; \bar{T}_W = \frac{T_W}{T_W^*}.$$

where T_{00} is the stagnation temperature in the center of the stream; D) diameter of the conduit; T_W^*) equilibrium temperature of the wall; T^*) stagnation temperature in the boundary layer; T_W) wall temperature; ρ_0, u_0) density and velocity of the gas in the center of the stream; q_W) thermal current at the wall; a_{00}, λ_{00}) coefficients of temperature conductivity and heat conductivity at stagnation temperature T_{00}; ρ, u) density and velocity of the gas in boundary layer.

From Eq. 1 we get

$$\mathrm{Pe}_{\theta}=\frac{\int\limits_{0}^{x} q_{wt}\,dx}{t_0\lambda_{00}}, \qquad (2)$$

or

$$\mathrm{Pe}_{\theta}=\frac{Q_x}{\pi D\lambda_{00}t_0}, \qquad (3)$$

where

$$Q_x=\int\limits_{0}^{x}\pi D q_{wt}\,dx.$$

We must find the parameters of the gas in the center of the stream in order to determine by experiment the local values of Stanton's criterion. If the static pressures along the conduit are measured, the parameters of the gas in the center of the current are immediately determined from the gas-dynamic functions. But if only thermal measurements are made in the experiments, we may then, with sufficient accuracy for the problem posed, take, as do Leont'yev and Fedorov [7],

$$\mathrm{Pe}_{\theta}=\mathrm{Pr}\,\mathrm{Re}_{\vartheta};$$
$$\mathrm{Re}_{\vartheta}=\frac{\rho_0 u_0\vartheta}{\mu_{00}}, \qquad (4)$$

where ϑ is the size of the loss of momentum. Then, using the discontinuity equation, we obtain (loc. cit.):

$$\frac{\rho_0 u_0 D}{\mu_{00}}=\mathrm{Re}_{D_1}+4h\mathrm{Re}_{\vartheta}, \qquad (5)$$

where $h=\dfrac{\int\limits_{0}^{\frac{D}{2}}\left(1-\frac{\rho u}{\rho_0 u_0}\right)dy}{\vartheta}$

and

$$\mathrm{St}=\frac{q_{wt}D}{(\mathrm{Re}_{D_1}+4h\,\mathrm{Re}_{\vartheta})\mathrm{Pr}\,\lambda_{00}t_0}, \qquad (6)$$

where $$\mathrm{Re}_{D_1} = \frac{\rho_{01} u_{01} D}{\mu_{00}}.$$

In subsonic and perisonic gas flow $h = 1.3\overline{T}_w$, which is known from the literature [5, 6,8]. Thus, based on the usual measurements made in experimental research on heat transfer we may from Eqs. 2 and 6, determine the local values of the Stanton and Péclét criteria and establish the law of heat exchange. The figure shows the results obtained from treating the experimental data on heat transfer in the initial section of a conduit on a plate and a cone in accordance with the proposed methods. The effect of anisothermicity and compressibility on the local values of Stanton's criteria is accounted for in accord with the equation suggested by Kutateladze and Leont'yev [9]. All the experimental points obtained for the various laws of heat supply in the different experimental set-ups have been placed on one curve, which may be described by the following equation:

$$\mathrm{St} = \frac{0{,}014(1-\beta^2)^{0{,}5}}{\mathrm{Pe}_\theta^{0{,}25} T_{wt}^{0{,}5} \mathrm{Pr}^{0{,}5}}, \qquad (7)$$

where $$\beta = \frac{u_0}{\sqrt{2c_p T_{00}}}.$$

Utilizing Eqs. 5 and 7 and integrating Eq. 1 we may obtain the solution for the cases where $\overline{T}_w$ = const and the law of heat supply is given, cp. Leont'yev and Fedorov [7].

The advantage of the proposed methods of generalization of the experimental data versus criterion treatment is our ability to exclude the effect which criterion $\overline{x}$, basically determining the distribution of the coefficients of heat transfer along the length of the conduit, exerts on the laws of heat transfer and to ascertain the effect of anisothermicity and compressibility in their pure form. In addition, the proposed law of heat transfer has a universal nature and all

the multiplicity of boundary conditions, i.e., the direct effect of $\bar{x}$ and of the law of heat supply on the distribution of local coefficients of heat transfer, are taken care of by the equation of the thermal boundary layer.

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